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Meaningful testing of fibre reinforced shotcrete for lining designs

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Meaningful Testing of Shotcrete

October 2019

Mr Des Vlietstra

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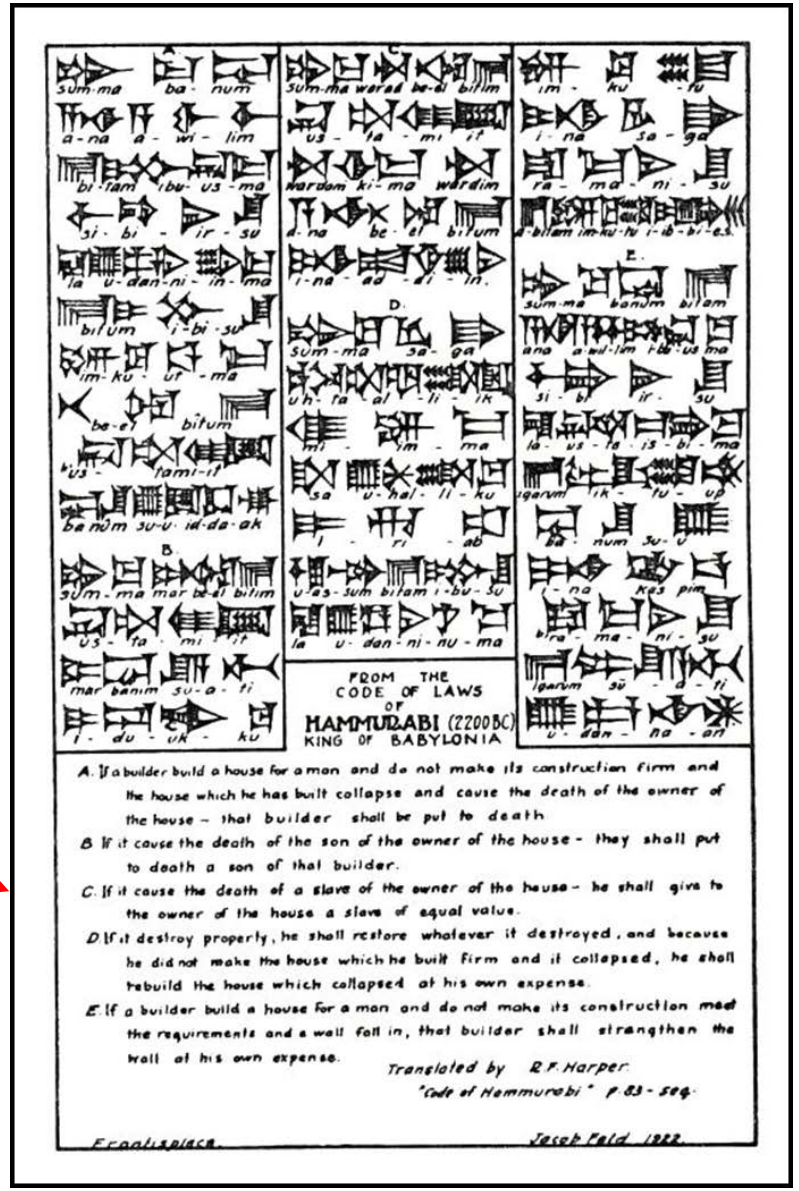
Testing

KING OF BABYLONIA

A. If a builder build a house for a man and do not make its construction firm and the house which he has built collapse and cause the death of the owner of the house – that builder shall be put to death

B. If it cause the death of the son of the owner of the house - they shall put to death a son of that builder.

C. If it cause the death of a slave of the owner of the house – he shall give to the owner of the house a slave of equal value.



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The Theory of Testing

Testing is simply asking a question of a material.

The answer of which should be:

- Relevant
- Meaningful
- Useful

If the answer is not all three points above then you need to seriously consider why the test was carried out.

Shotcrete Testing

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"Testing leads to failure, and failure leads to understanding."
Burt Rutan

- *Development - Investigating available materials with a view to economies.*
- *Quality Assurance – Planned systematic actions assuring shotcrete will meet users needs.*
- *Quality Control – Measure and control the materials and processes in supply and application.*
- *Investigative – Testing required in response to defective or non-compliant shotcrete.*

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Requirements for a Relevant Test

- Correct Sampling
- Test the actual mix
- Specimen preparation
- Specimen treatment
- Correct equipment
- Correct testing procedures
- Standards

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Sampling

Spot Sample

or

Composite Sample

Representative

Increments totally mixed

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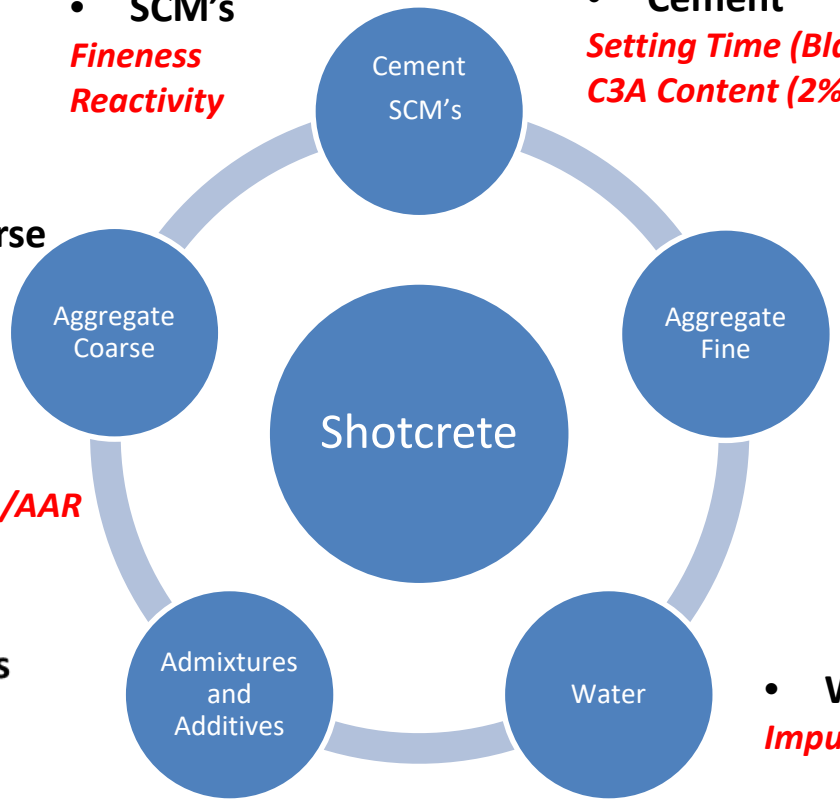
Raw Materials

(Testing)

- **SCM's**
  Fineness
  Reactivity

- **Cement**
  Setting Time (Blaine 340-420)
  C3A Content (2% -10%)

- **Aggregate – Coarse**
  Density
  Strength
  Grading
  Shape
  Absorption
  Cleanliness/Soundness/AAR



- **Aggregate – Fine**
  Density
  Grading
  Moisture Content
  Clay and Silt Content

- **Admixtures**
  Specific Gravity
  Homogeneity

- **Water**
  Impurities



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General and Organic Impurity Tests

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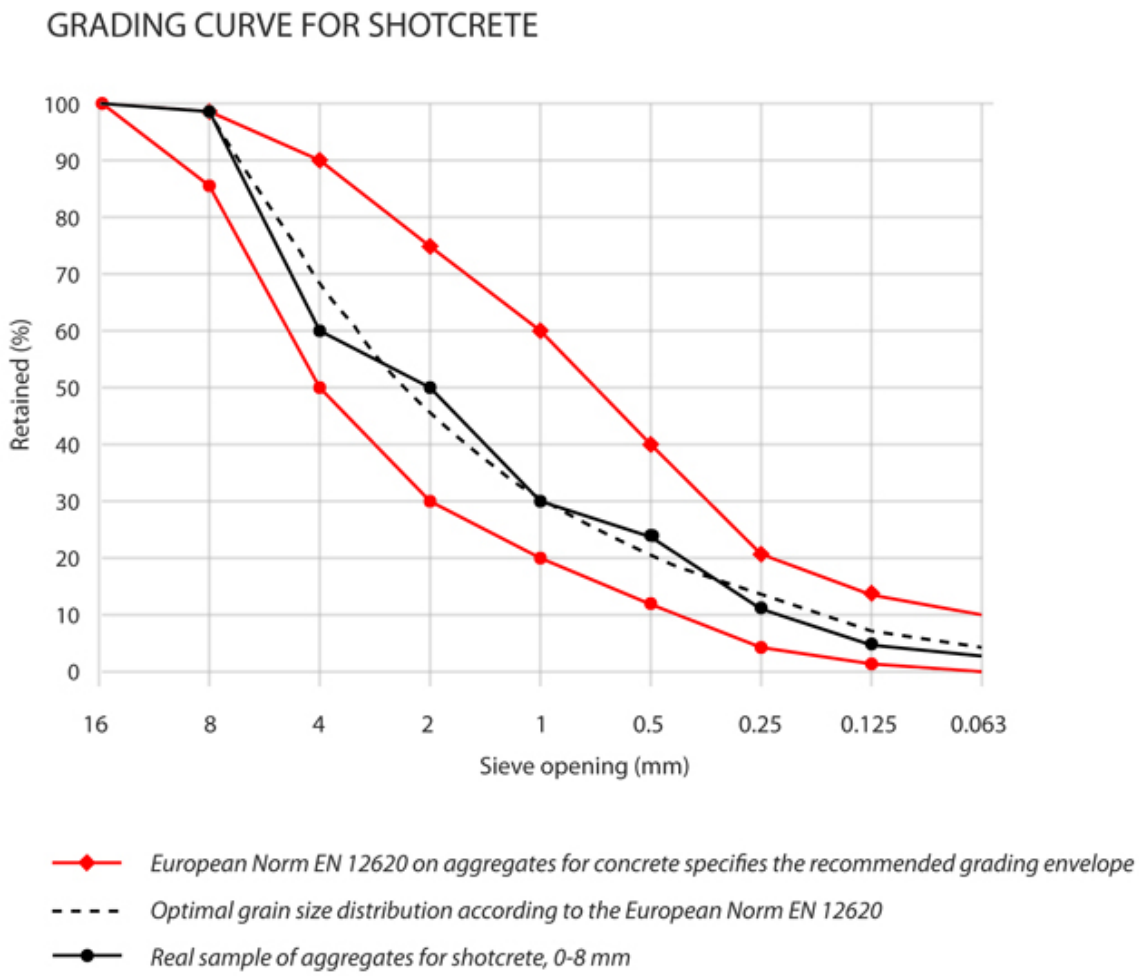
Raw Materials

(Testing)



Mix Development

(Testing)

Material(s) Testing confirms appropriateness of each component for use in the manufacture of Shotcrete

Water/Cementitious Ratio determined and mix proportioned based on density and combined grading

Trial mix made to test the design and capture the Wet, Green and Hardened properties of the mix

Slump Test

Consistency

Compressive Strength

Characteristic Strength

Flexural Strength

Tensile Strength in Flexure

Indirect Tensile Strength

Tension at 90^{o} to direction of force

Drying Shrinkage

Length Change reported in microstrain

Air Content

Determination of Air Content

Mass per Unit Volume of Fresh Concrete

Yield of design

Bleeding

Rate and total volume of bleed water

Mass per Unit Volume of Hardened Concrete

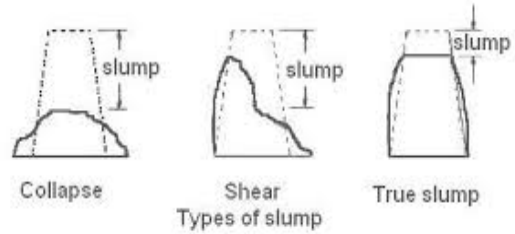
Measures the dry density of the concrete

Setting Time

Determination of setting time by penetration resistance

Slump Test

- Amount of subsidence from original height constitutes “Measured Slump”
- Taken after a minimum of 0.2 M^3 has been discharged from mixer
- Level ‘pre-wetted’ cone is filled in three layers with rodding after each addition
- Cone is removed in a smooth vertical action by tester
- Tolerance increases with increasing nominated value
- Rejection available





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Air Content and Yield

- Yield typically aimed at 98%
- Shotcrete made by weight but sold by volume – materials density
- Air content variable dependent on in service shotcrete requirements
- Air content reduced by pumping and again reduced by spraying

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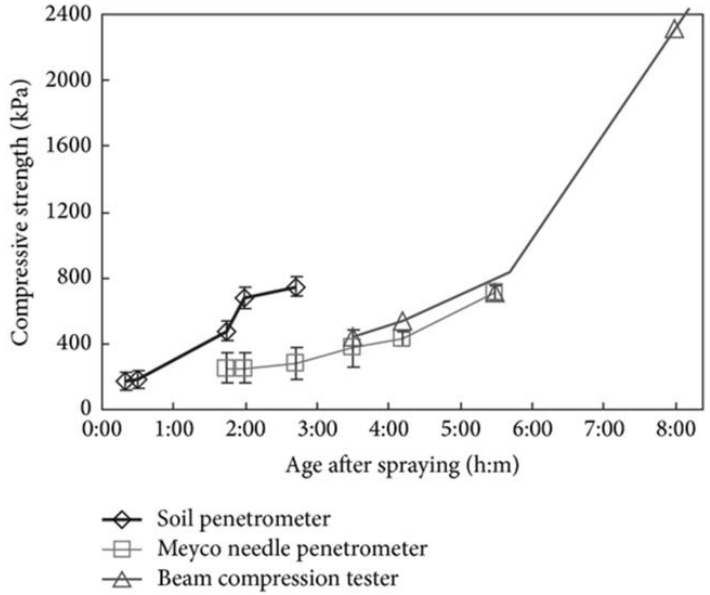
Early Age Strength Testing

- Soil penetrometer tends to over-estimate strength (0-0.5 MPa)
- Needle penetrometer effected by aggregate and fibre (0 – 1.0 MPa)
- Hilti gun method accurate but powered by charges (2-18 MPa)
- End-Beam tester accurate assessment and simple (0.5 – 8.0 MPa)



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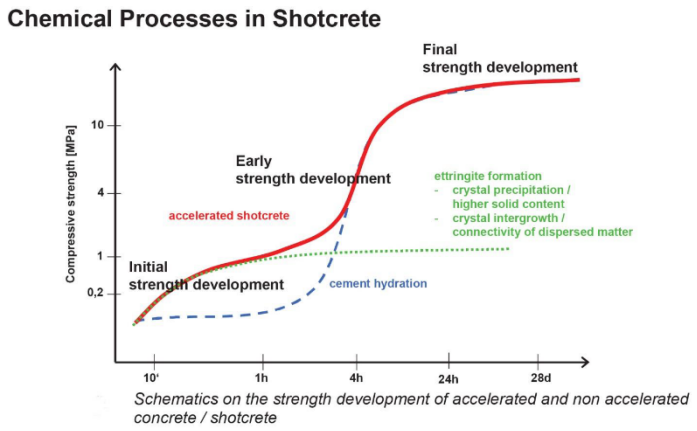
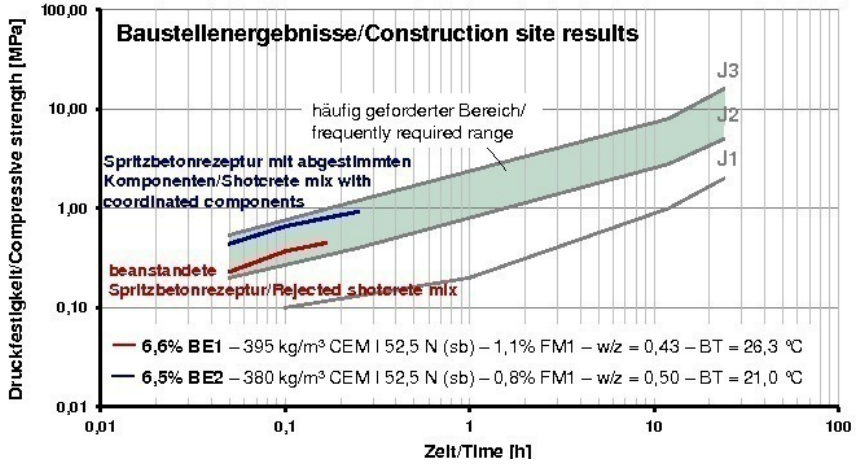
Early Age Strength Testing

- **Maturity in specimens should mimic in-situ conditions**
- **Austrian J charts (below) use cube strength**
- **Re-Entry generally >1.0 MPa**
- **Assumptions are……..**



Schematics on the strength development of accelerated and non accelerated concrete / shotcrete



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Testing Compressive Strength

Cylinders or Cubes

- Cylinders filled in three stages with 25 hand rods incorporating each addition
- Protected from disturbance and evaporation
- Indicate ‘potential’ achievable






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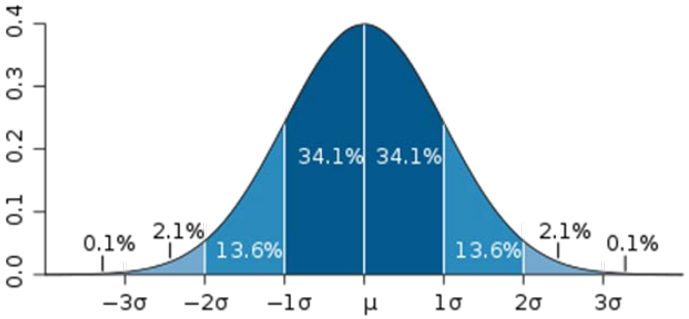
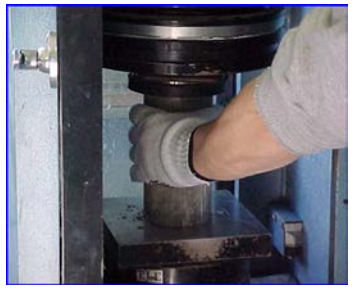
Testing Compressive Strength

(Cast Cylinders)

- **Density**
- **Pair difference**
- **Failure Type**



Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for about 68% of the set (dark blue), while two standard deviations from the mean (medium and dark blue) account for about 95%, and three standard deviations (light, medium, and dark blue) account for about 99.7%.



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Testing Compressive Strength

- Care must be taken not to damage specimens during extraction
- Visual indicator of spraying efficiencies
- Must be temperature match conditions if direct comparison to cast cylinders is sought
- Inspection of embedded reinforcement
- Building a picture






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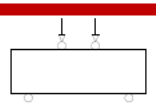
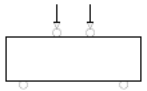
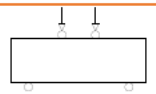
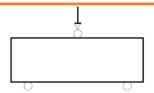
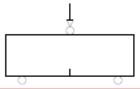
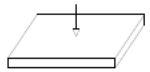
Standard test method characteristics

TEST	SCHEME	Volume (cm^3)	Failure area (cm^2)	Specific Failure area	CV (%)
4-point bending test (ASTM C-1018)		3,500	10x10 = 100	0.0286	15
4-point bending test (NBN B 15-238)		16,875	15x15 = 225	0.0133	12-20
4-point bending test (EFNARC)		5,156	7.5x12.5 = 93.8	0.0182	20
3-point bending test		5,156	7.5x12.5 = 93.8	0.0182	17
3-point bending test (RILEM)		12,375	15x12.5 = 187.5	0.0152	15-25
EFNARC Panel		36,000	8x(32.5x10) = 2.597.7	0.0722	9
Round determinate panel test		37,700	3x(40x7.5) = 900	0.0238	6-13
Double punching test (DPT) BCN		2,650	3x(7.5x15) = 337.5	0.1274	13

[Molins et al., M&S 2009]

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Particulars of standard beam tests – Geometry

Country	Standard	Length [mm]	Span s [mm]	Width [mm]	Depth [mm]	Weight [kg]	W [cm^3]	W/s [cm^2]
JP	JCI SF-4	550	450	150	150	29.7	562.5	12.5
US	ASTM C1609	550	450	150	150	29.7	562.5	12.5
FR	NF	500	420	140	140	23.5	457.3	10.9
DE	DBV	700	600	150	150	37.8	562.5	9.4
Int'l	RILEM/EN 14651	550	500	150	125	24.8	390.6	7.8
US	ASTM C1399	350	300	100	100	8.4	166.7	5.6
Int'l	EFNARC	550	450	125	75	12.4	117.2	2.6

Note: ASTM C1018-97 was withdrawn without replacement in 2006

W = section modulus
W/s = stiffness characteristic

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Standard beam testing speeds (closed loop)

- Closed loop means *displacement controlled*
- Movement of the test machine is controlled by the displacement reading (CMOD or deflection δ [mm])
- Criterion: constant increase of CMOD or δ per time unit [mm/sec] (testing speed)

	Displacement range from …	… to	Speed	Duration	Data logging	Data sets
	[mm]	[mm]	[mm/min]	[min]	[min. Hz]	[-]
EN 14651	0	0.1	0.05	2	5	600
(CMOD)	0.1	4	0.2	19.5	1	1170
				21.5		1770
ASTM C 1609	0	0.5	0.05	10	5	3000
(delta)	0.5	3.5	0.2	15	1	900
				25		3900

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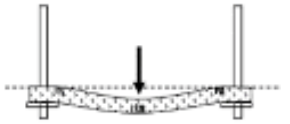
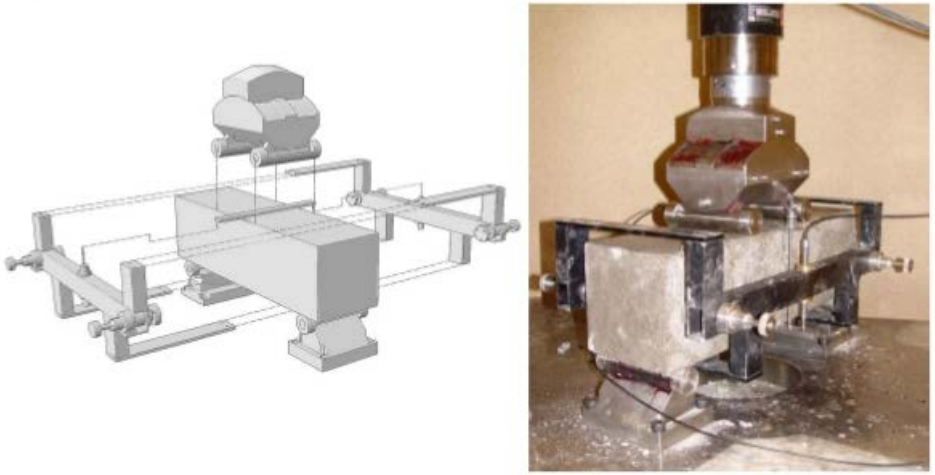
Residual Strength Testing

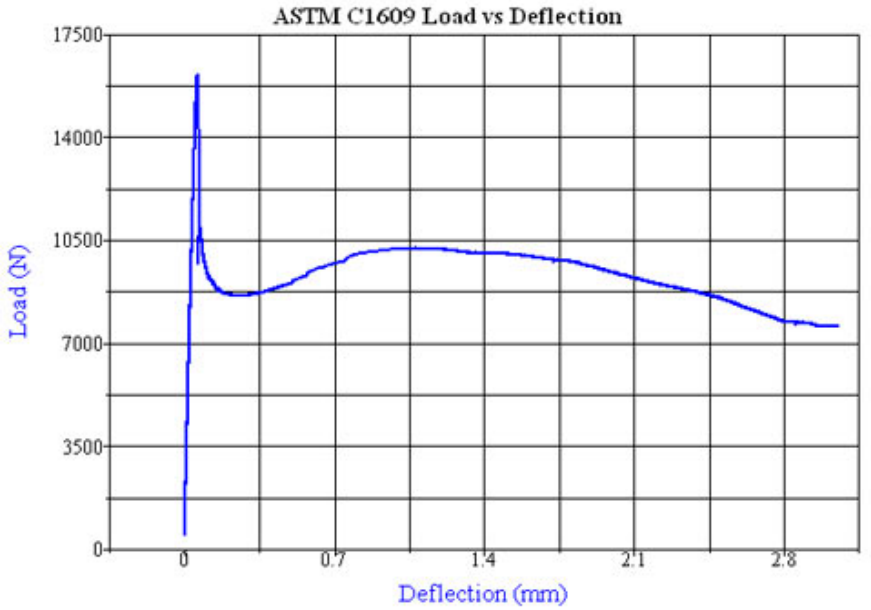
(Beam) ASTM C-1609

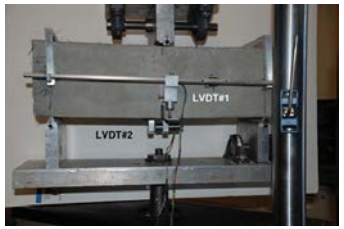




ASTM C-1609 tests involve no notch, no 'standard' concrete, cheaper to perform due to simpler test set-up

- **Sets of 3 (min)**
- **High Variability**
- **Difficult to measure performance change**





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ASTM C1609

ASTM C1609 / C1609M – 19 (2019)

- *Four point loading test*
- *Third point loading test*
- ASTM C 1609 utilizes two preferred specimen sizes: 100x100x300 and 150x150x450 [mm] (paragraph 1.3).
- Paragraph 7.1.4 says you have to use 150mm beams when using fibres of 50-75mm of length.
- No defined crack location:
- ➔ crack can be offset (different crack width)
- ➔ crack plane can be inclined

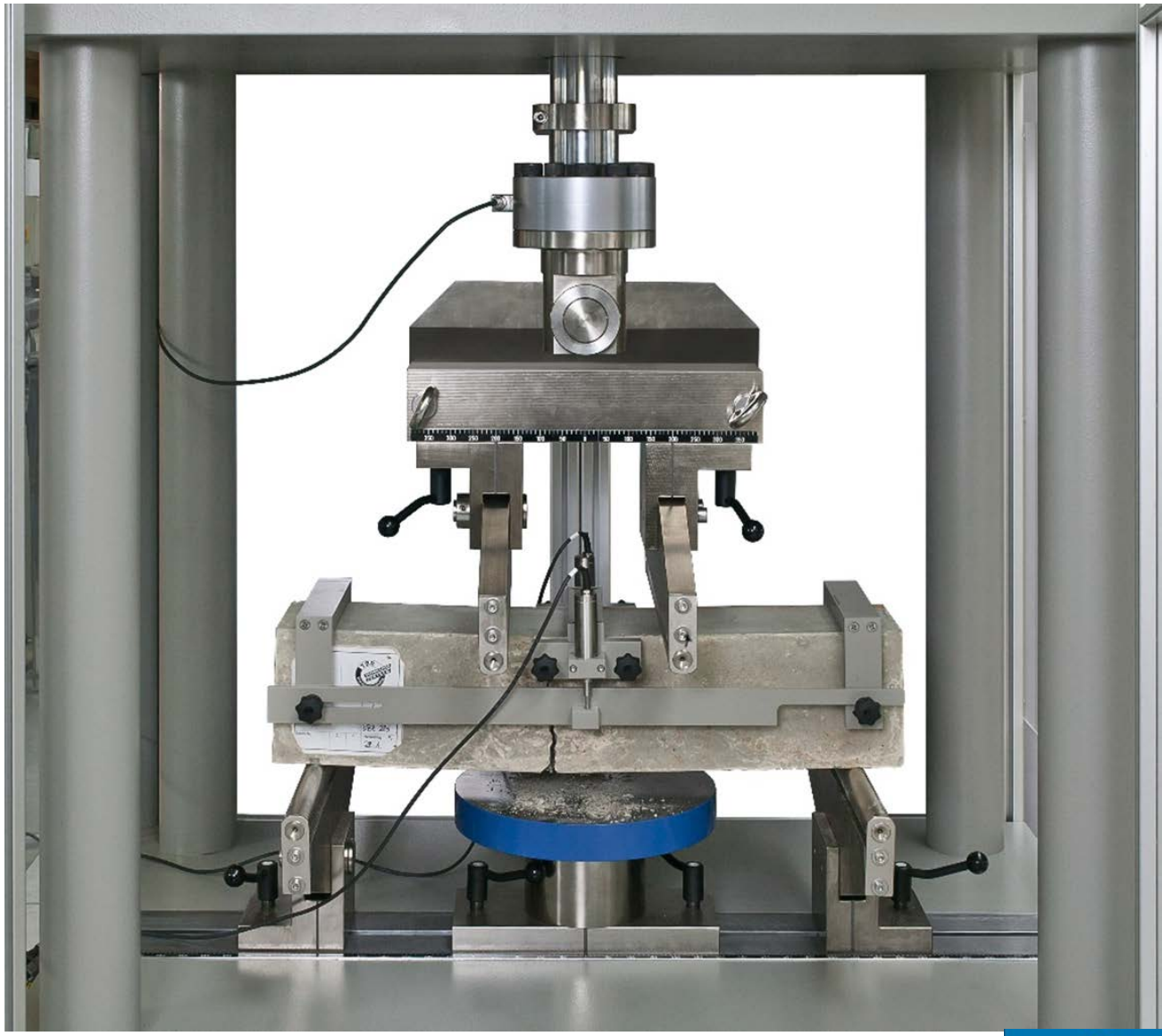

Photo credit - Hans-Heinrich Reuter

TESTING Baustoffprüfgeräte

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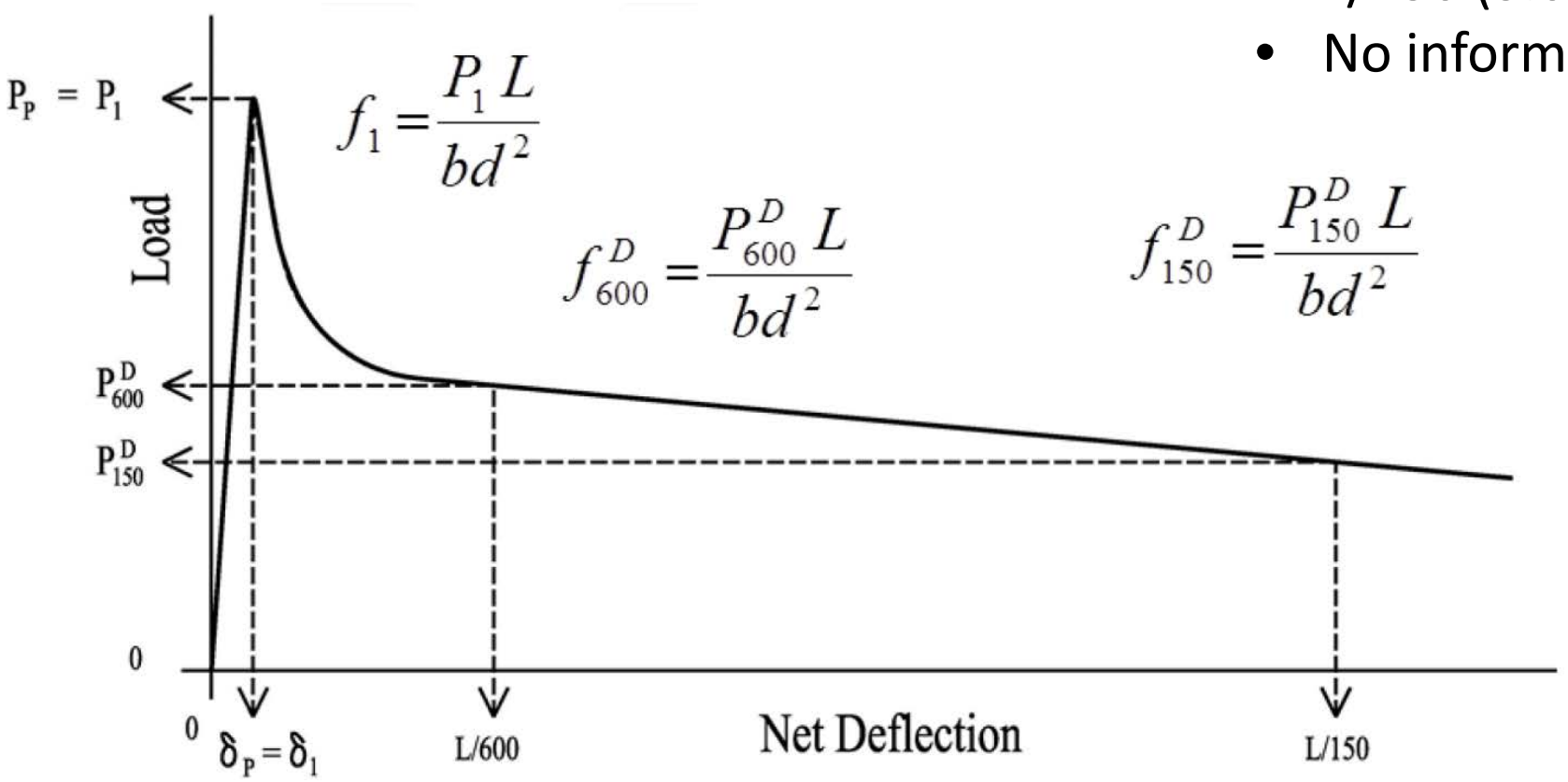
ASTM C1609

Exploitation at two stages of deformation

- L/600 (0.75 or 0.50 mm) – SLS
- L/150 (3.0 or 2.0 mm) – ULS
- No information on crack widths



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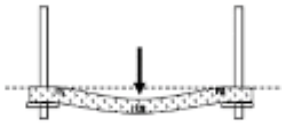
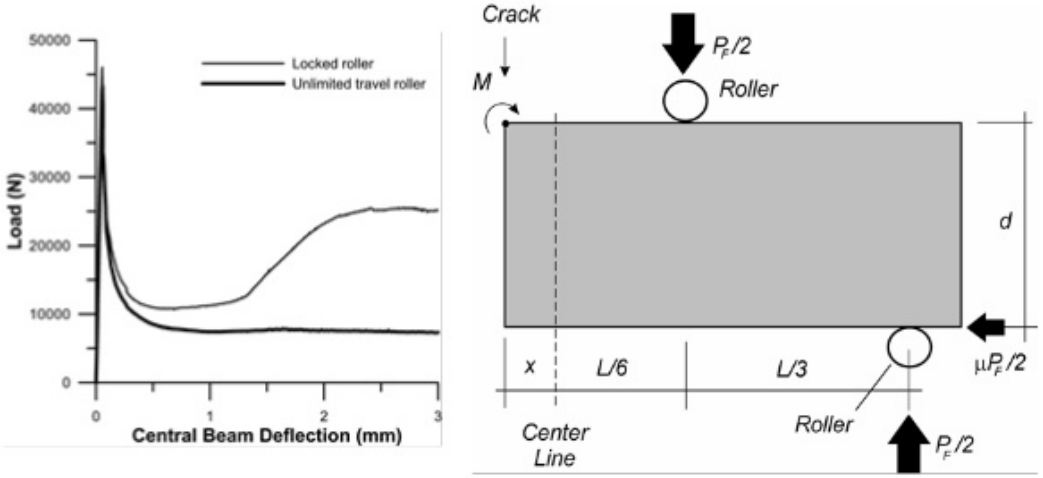
Residual Strength Testing

(Beam)

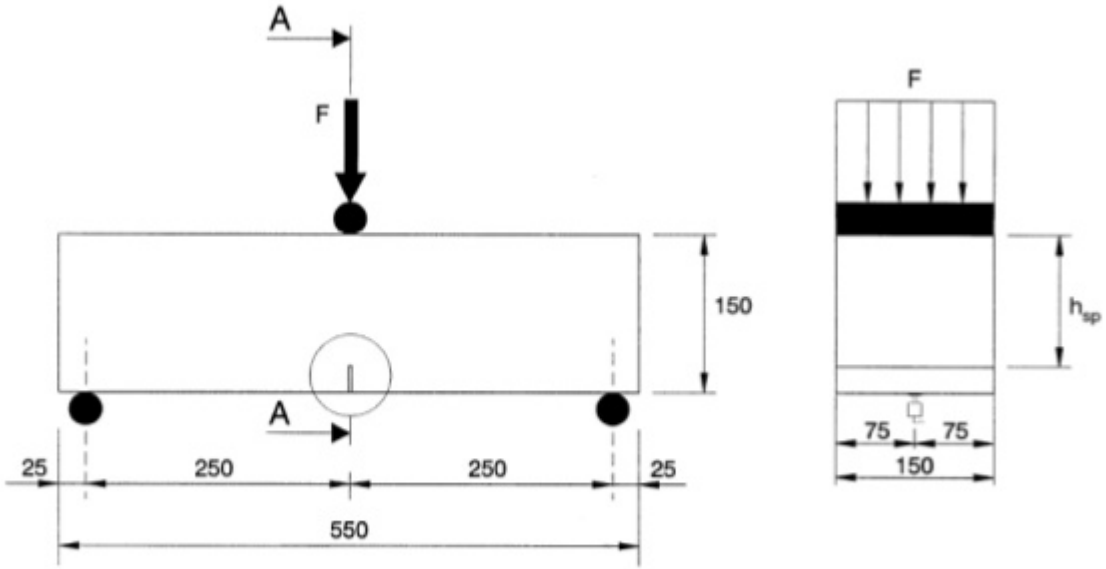


ASTM C- 1609 support rollers



Friction in supporting rollers can lead to very high bias in residual strength results of over 200% over-estimate

EN 14561 Beam Test



Central point load and notch lead to higher estimates of performance than are achieved with ASTM C1609.

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EN 14651 standard beam test

Harmonized European standard EN 14651 (June 2005)

"Test method for metallic fibered concrete"

- The beam testing principles of RILEM TC 162-TDF (2003) have been adopted in the harmonized European standard EN 14651
- Adopted by Model Code 2010

OFFICINE MACCAFERRI SPA - 2006 - 441786 - eco

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 14651

June 2005

ICS 91.100.30

English version

Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual)

Méthode d'essai du béton de fibres métalliques - Mesurage de la résistance à la traction par flexion (limite de proportionnalité (LOP), résistance résiduelle)

Prüfverfahren für Beton mit metallischen Fasern - Bestimmung der Biegezugfestigkeit (Proportionalitätsgrenze, residuelle Biegezugfestigkeit)

This European Standard was approved by CEN on 3 April 2006.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 14651:2005: E

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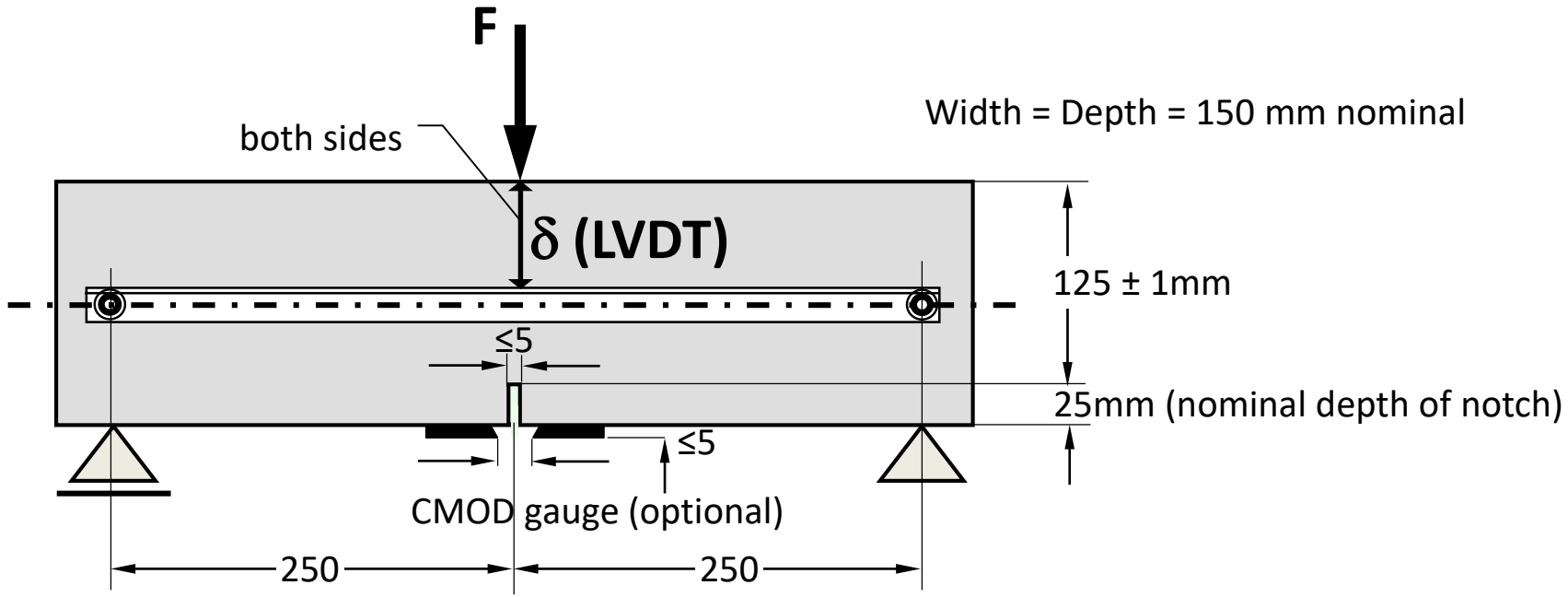
EN 14651 beam test

Bending test according to EN 14651:2005

3-point loading test with notch (crack inducer)



Increase of CMOD/mid-span deflection: 0.05/0.2 mm/min
Deflection in minimum up to 3.0 mm (3.5mm CMOD)

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EN 14651 beam test

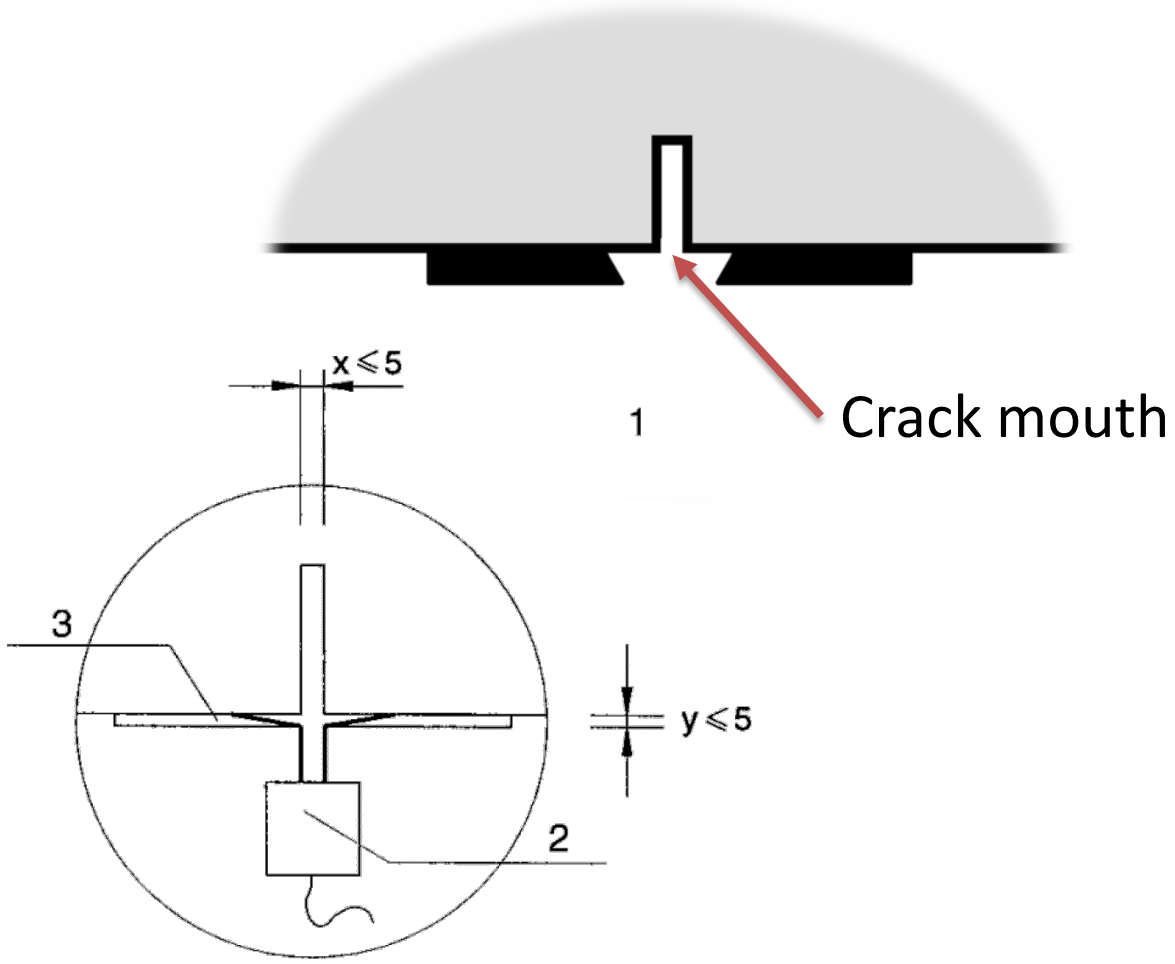
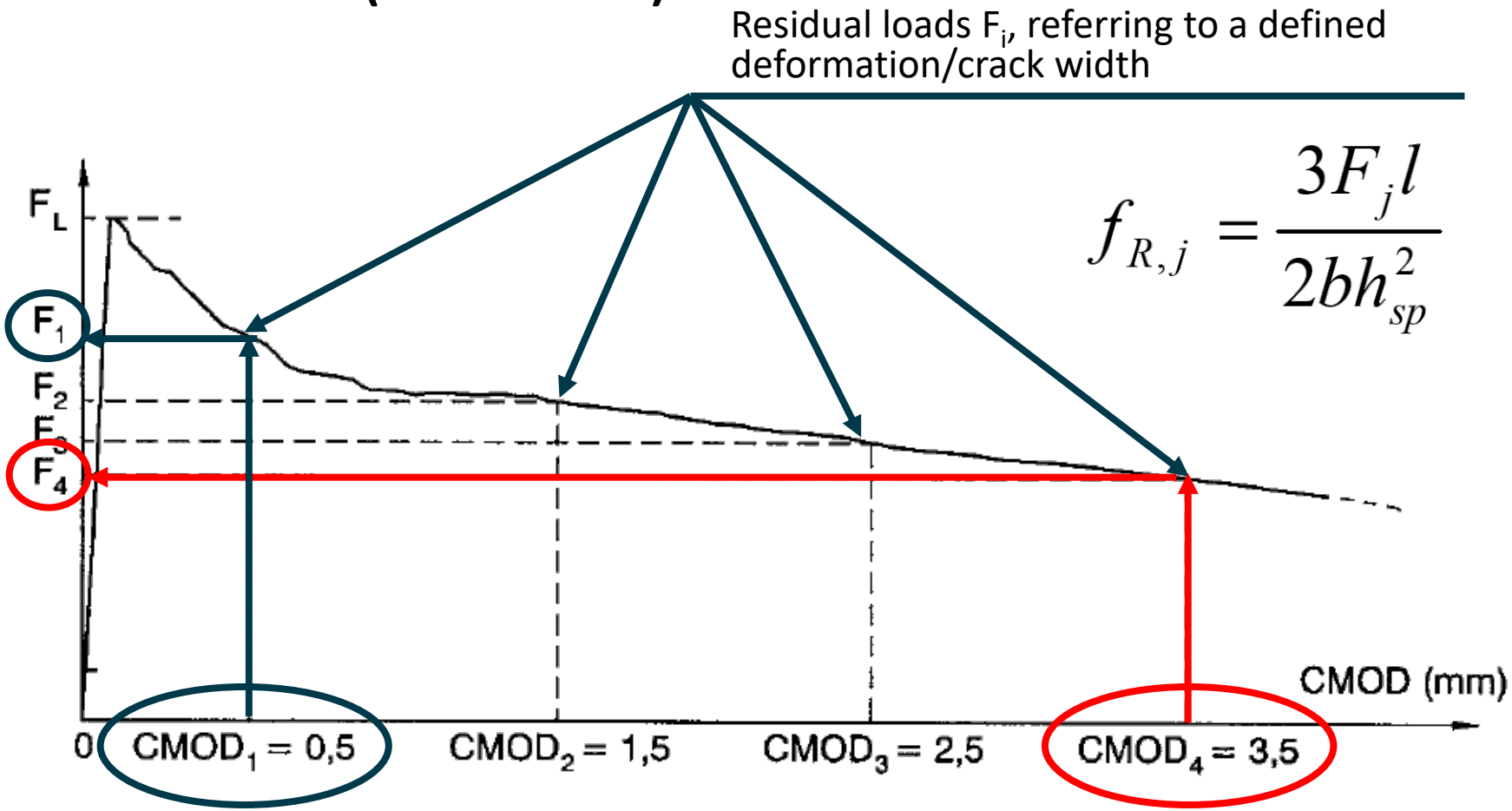


Table 1 – Relationship between *CMOD* and δ

CMOD (mm)	δ (mm)
0,05	0,08
0,1	0,13
0,2	0,21
0,5	0,47
1,5	1,32
2,5	2,17
3,5	3,02
4,0	3,44

Residual flexural strength

EN 14651:2005 (RILEM 2003)



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FRC tensile design values

Plain concrete (TR34/4):

$$f_{ctd,fl} = f_{ctm} \times (1.6 - h / 1000) / \gamma_m$$

Fibre reinforced concrete (RILEM, TR34/4):

$$\sigma_{r1} = 0.45\, f_{R1}$$

$$\sigma_{r4} = 0.37\, f_{R4}$$

f_{R1} = the residual flexural strength at CMOD 0.5mm

f_{R4} = the residual flexural strength at CMOD 3.5mm

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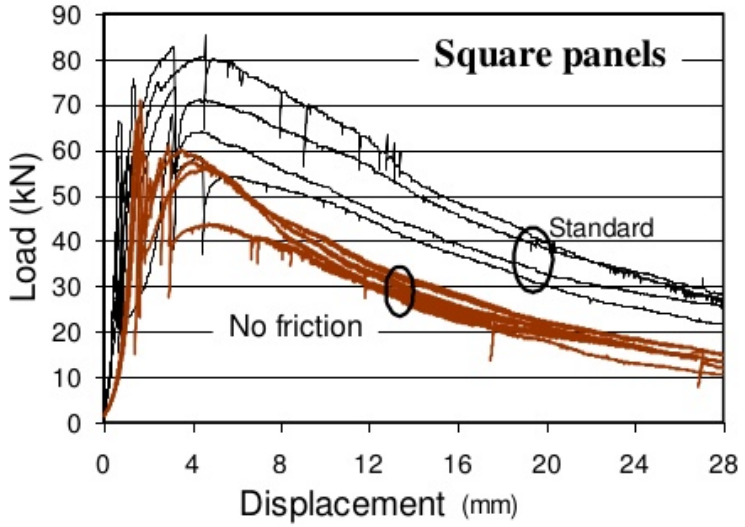
Residual Strength Testing

- **EN 14488 Square Panel**



Research in Norway demonstrated that friction with supports is responsible for about 40% of energy absorption

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Panel testing

- Panel testing is standard for temporary shotcrete linings
- Panel tests are more representative for in-situ linings
- Statically indeterminate, i.e. no strain localization, stress-redistribution and multiple cracking is possible
- MSF superior to SF at larger crack widths (longer fibres sprayable)

- Final lining design prefers beam test results (traditional civil engineering)
- MSF inferior to SF in beam tests (small displacements, low fibre stiffness)
- Push panel testing, avoid beam testing!

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Square panel test

Panel dimensions:
600 × 600 × 100 [mm]

Load contact area:
100 × 100 [mm]

- EFNARC (1996)
- EN 14487-1:2005 and EN 14488-5:2006
- Energy absorption punching test
- Machine controlled, no closed loop
- Sprayed side down (EFNARC)
- Steel frame continuous support
- Statically indeterminate (hyperstatic), allowing stress redistribution and multiple cracking
- Yields no design values

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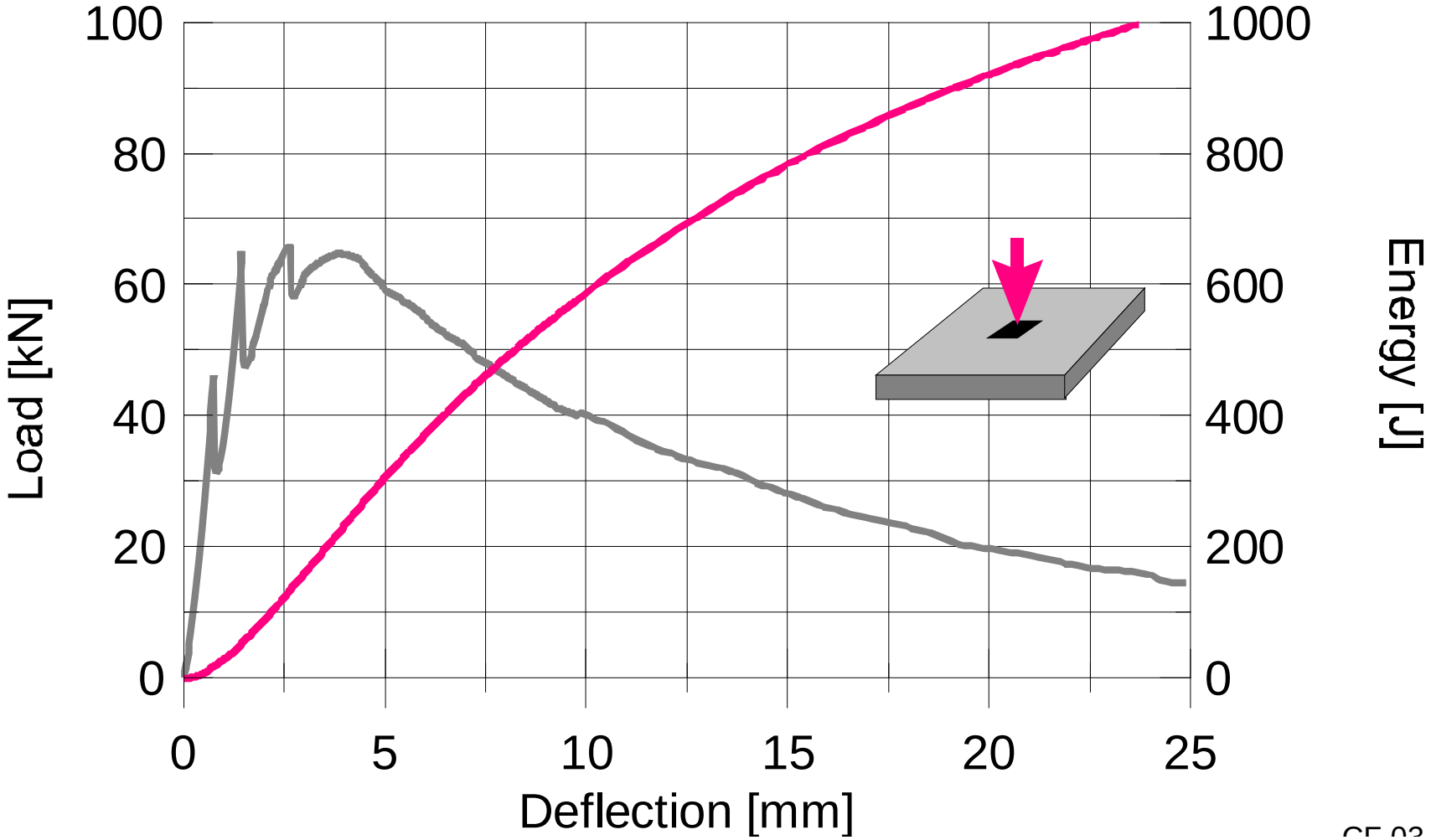
Square panel test results



Integrate the load-displacement curve (determine the area under the curve) to obtain the energy absorbed in [Nm]

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Influence of fibre dose rate

- The resulting crack patterns of the panels depend on the fibre dose rate (BC48)
- Higher rotation capacity and more cracks appear by increasing the fibre dosage

Plain concrete | 2.5 kg | 5.0 kg | 7.5 kg

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Panel test result classification

SFRS performance classes

- EFNARC: European specification for sprayed concrete, 1996 (A, B or C)
- EN 14487-1:2005 Sprayed concrete - Definitions, specifications and conformity (Exxx)
- Results valid for panel thickness of 100 to 105mm (0% to 5% over)

Toughness classification	Energy absorption @ 25mm deflection
A / E500	**500 Joules**
B / E700	**700 Joules**
C / E1000	**1000 Joules**

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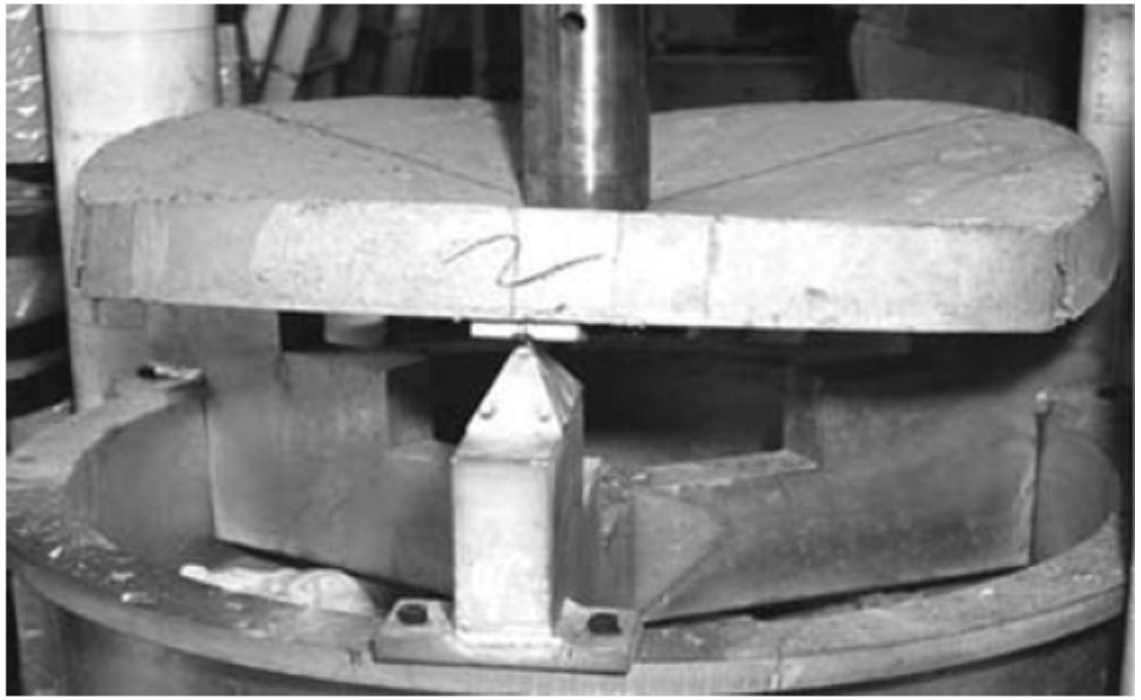
Round Determinate Panel Test (RDPT)



- ASTM C 1550-12a
- Statically determinate system (3 defined fracture lines)

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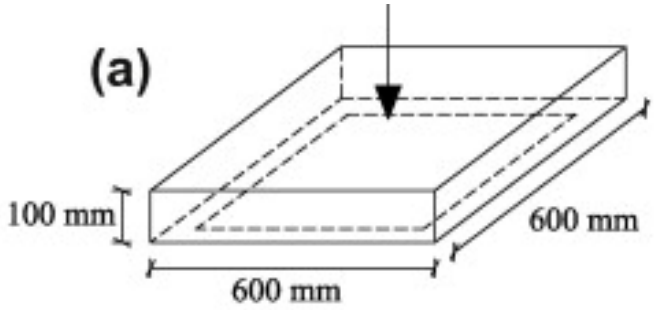
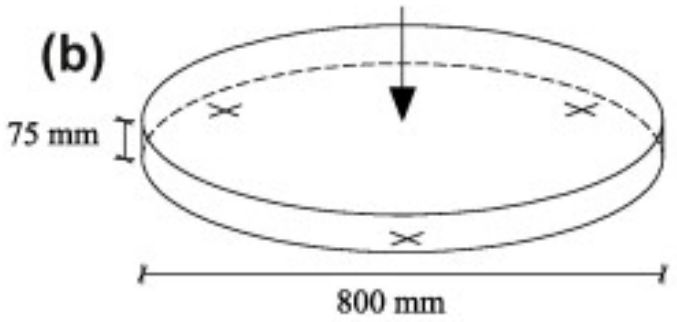
Panel test characteristics





Variability:	COV's of less than 15%	COV's of 10% or lower can be achieved
Friction:	up to 35%	approx. 12.5%
Crack length:	up to approx. 2600 mm (8 cracks)	1200 mm (3 pre-determined cracks, from centre)

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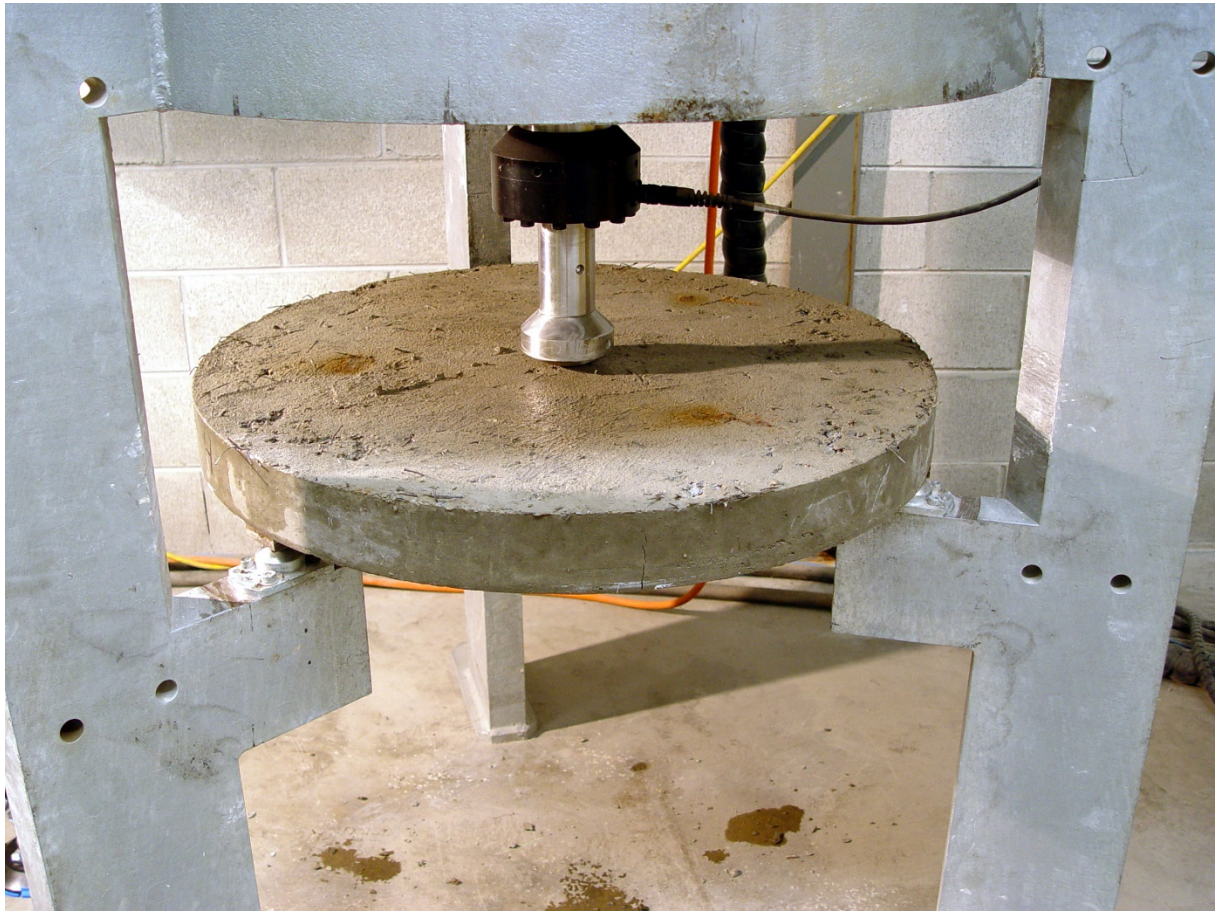
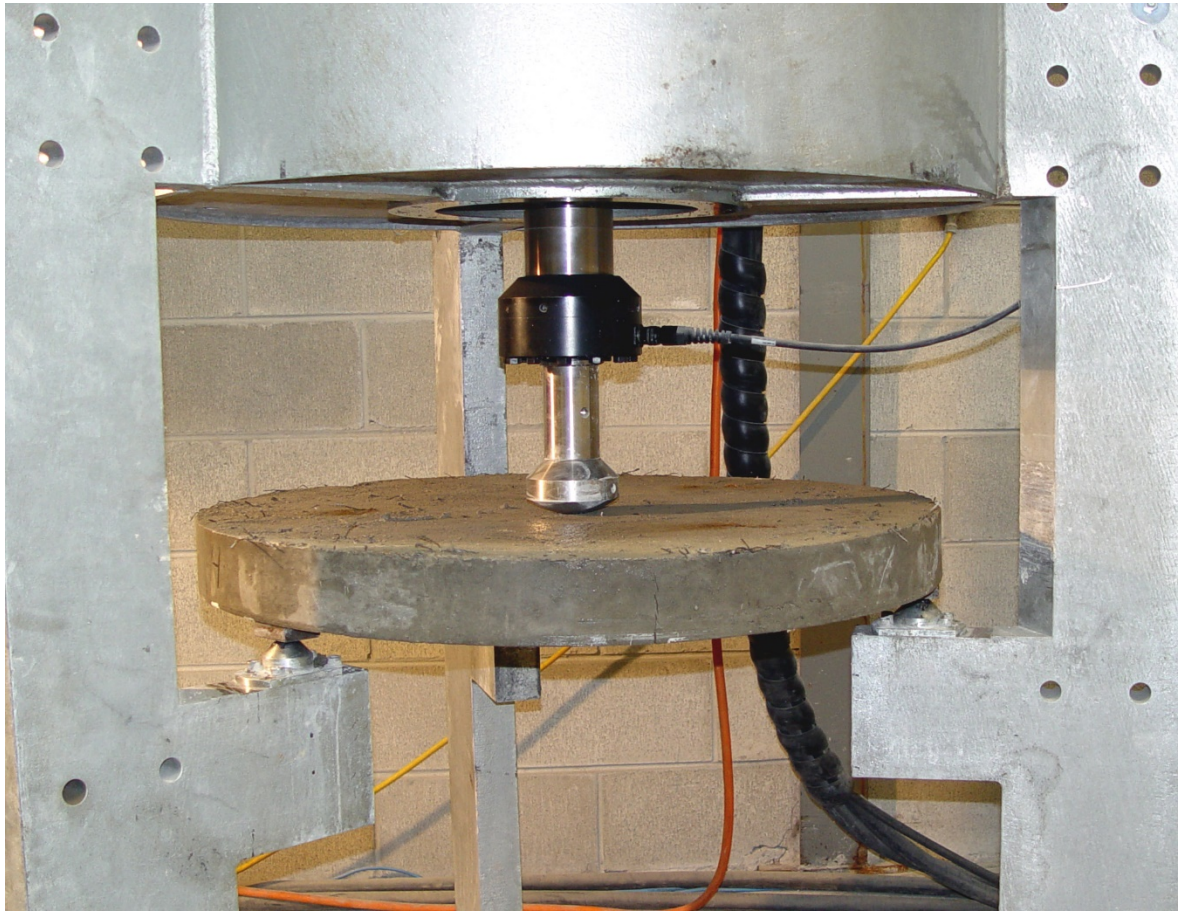
Round Determinate Panel Testing





TSE setup: MTS Flextest GT controller, MTS 244 100 kN actuator. LVDT and load cell included in system.

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RDP: Development of 3 defined cracks

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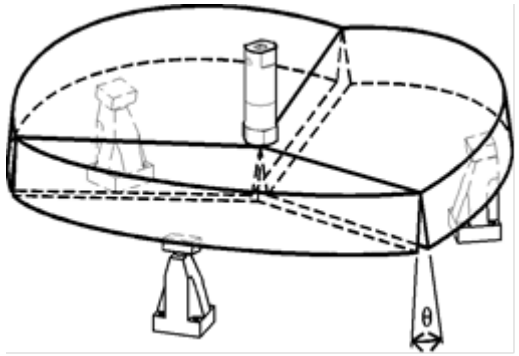
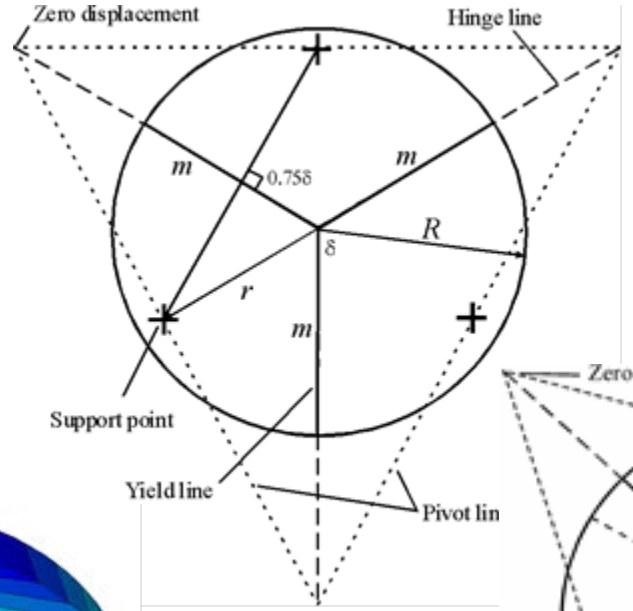
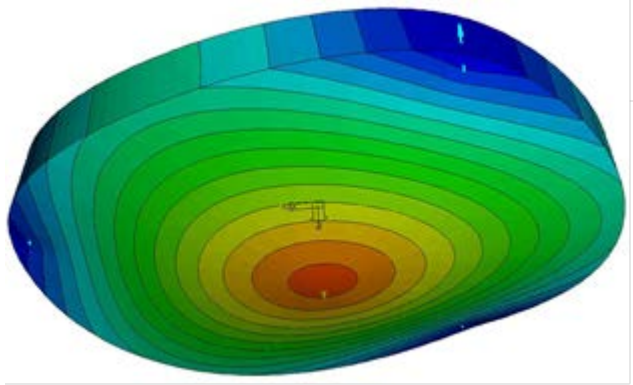
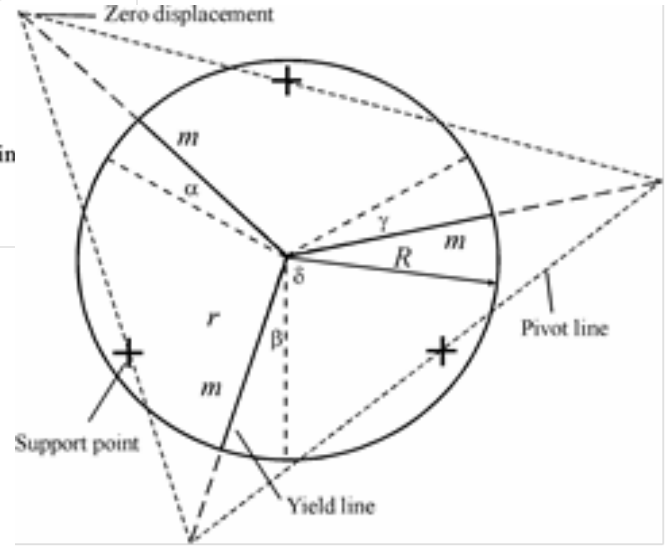
Analysis of the Round Panel Test









The ASTM C1550 round panel has been extensively analysed to determine how the results of this test are related to the performance of FRS in tunnels and FRC in pavements. Data indicates that Yield Line analysis based on un-notched beams is very accurate.

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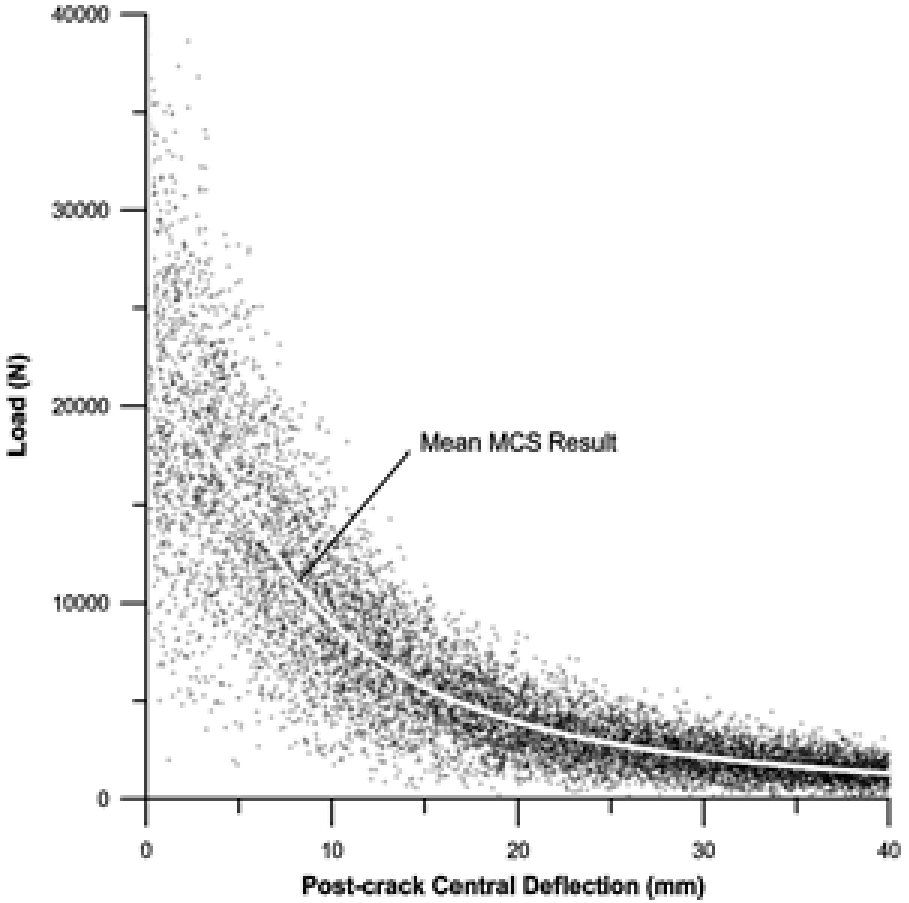
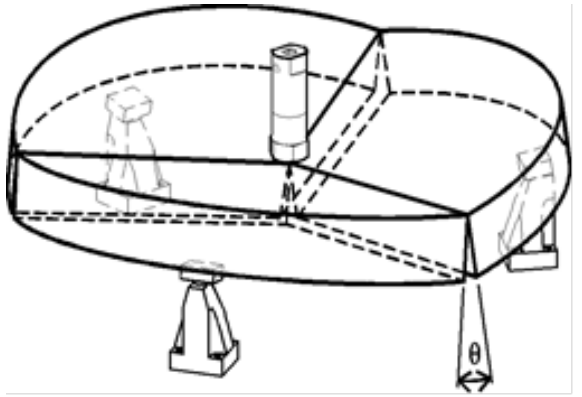
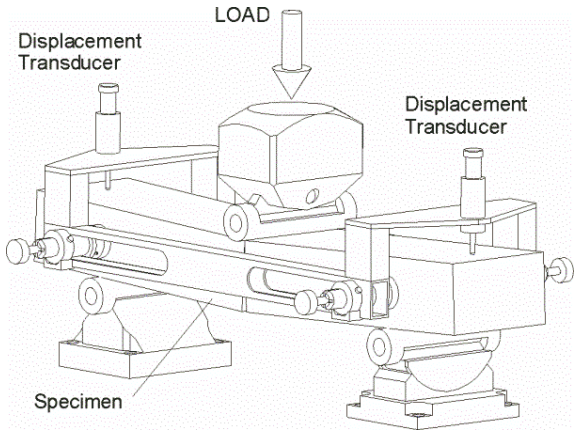
Analysis of the Round Panel Test







Yield Line analysis of ASTM C1550 round panels indicates that beam results are useful in predicting accurate estimates of both the cracking load and post-crack performance, but apparent ‘useable’ cracking load is sensitive to toughness immediately after cracking.

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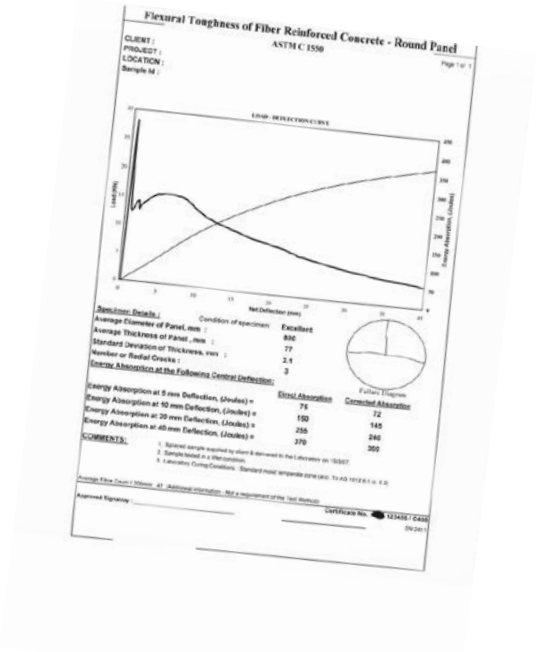
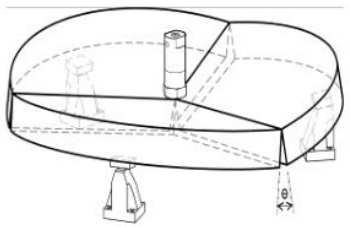
Residual Strength Testing

(Round Determinate Panel) ASTM C 1550

- Sets of three advised
- Method of failure important analysis
- Safety in numbers……





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Residual Strength Testing

(Round Determinate Panel) ASTM C 1550

- RDP moulds should be inclined against a wall at between 45 – 60 degrees ensure they are stable and not able to move.
- The moulds must be clean free of gravel, mud rock etc.
- Inside should be wiped with form release oil (Can also use hydraulic oil)

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Residual Strength Testing

(Round Determinate Panel) ASTM C 1550

- Panel can be upright or horizontal
- Screed the panel level with the with the topmost edge of the mould
- Best using a 1.2m aluminium screed in a zig zag motion whilst dragging the screed across the panel
- If screed catches on fibres and causes a divot of shotcrete to come out replace immediately with a handful of shotcrete and screed level again
- Use a shovel or pelican pick to clean the shotcrete around the panel, pay special attention to the bolts
- Panel must be floated smooth best done with either a moist timber or magnesium float with curved sides.
- Clearly spray details on panel (Date, code, decline etc)

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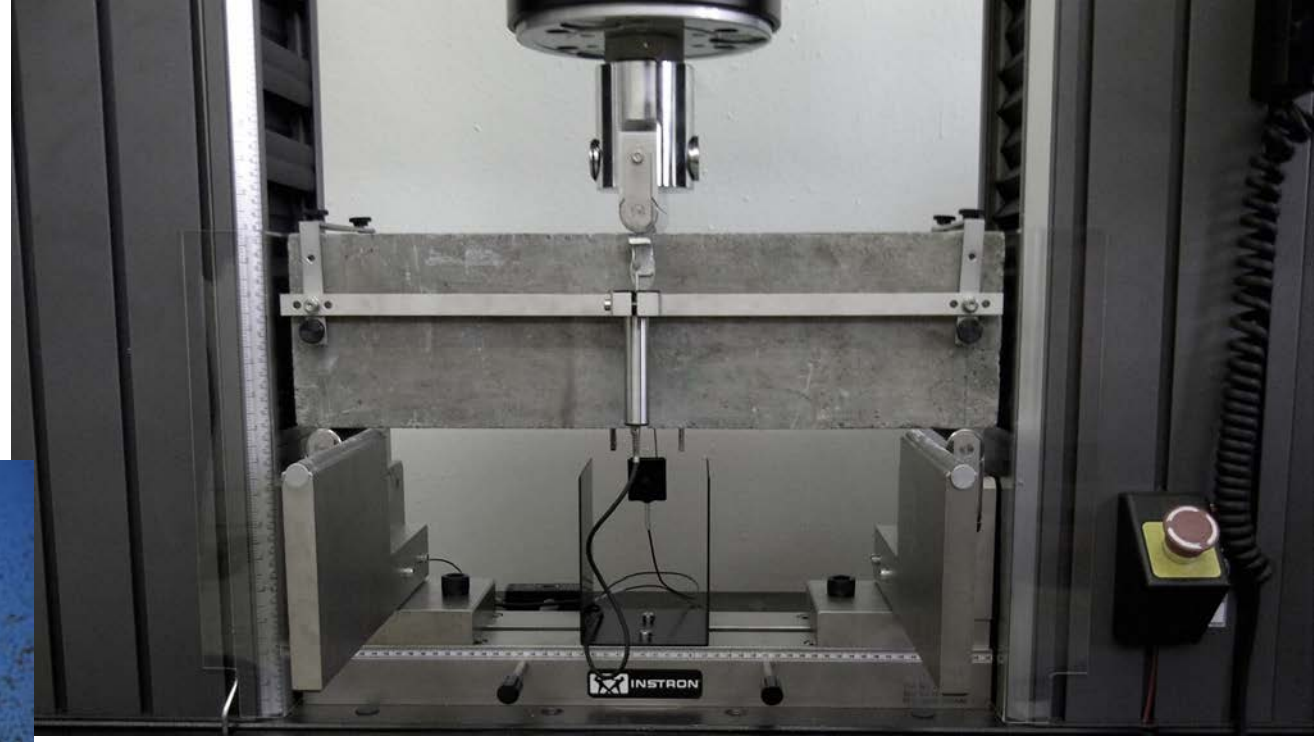

Thank You